RGS Focal Plane Camera (RFC) Technology Status

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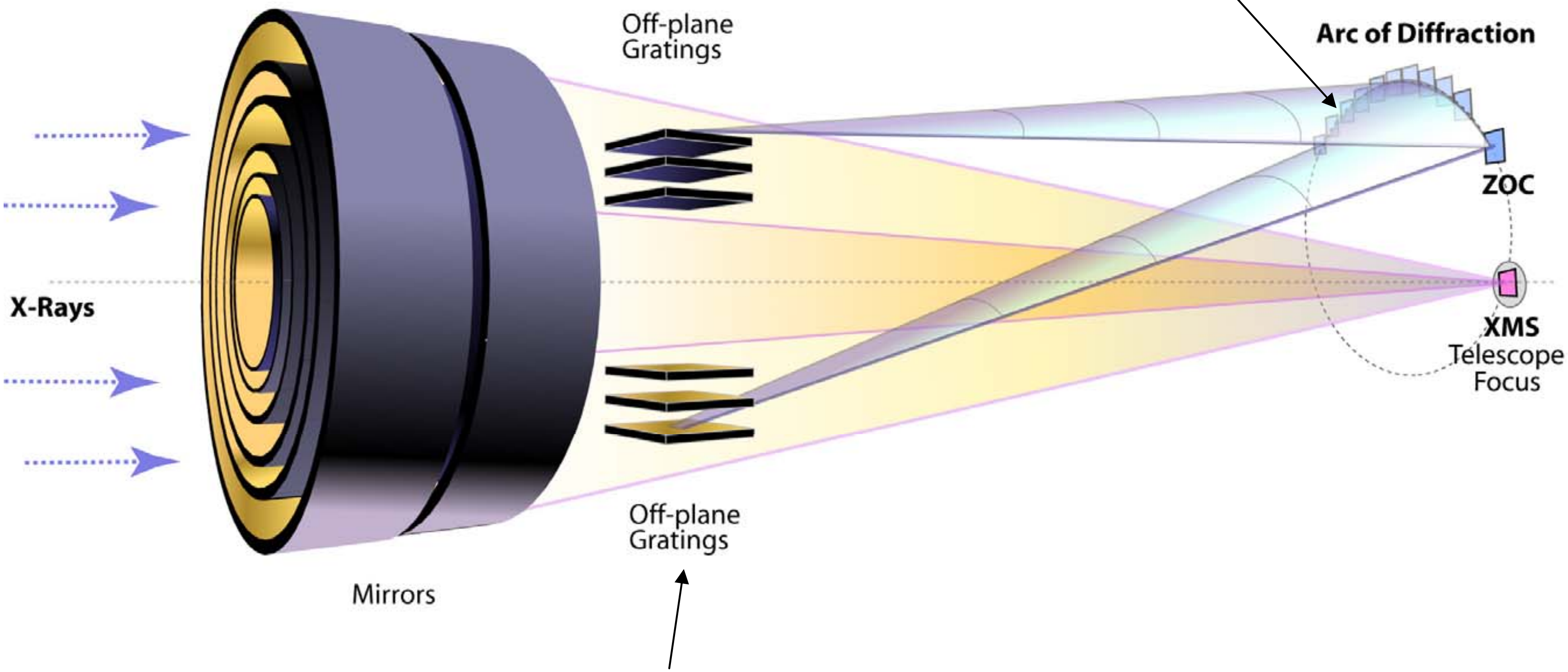
Reflection Grating Spectrometer (RGS) Overview

- **A grating spectrometer is needed to satisfy the spectral resolution requirements at low energies.**
- **The Reflection Grating Spectrometer (RGS) is an array of co-aligned reflection gratings (RGA) that disperse x-rays to the *RGS Focal Plane Camera* (RFC), an array of back-illuminated CCD detectors.**
- **The RFC consists of two camera systems: the Spectroscopy Readout Camera (SRC) and zero-order camera (ZOC). The SRC images the dispersed spectrum while the ZOC reads out the reflected image. The ZOC anchors the wavelength scale by tracking small aspect drifts.**

Reflection Grating Spectrometer Overview

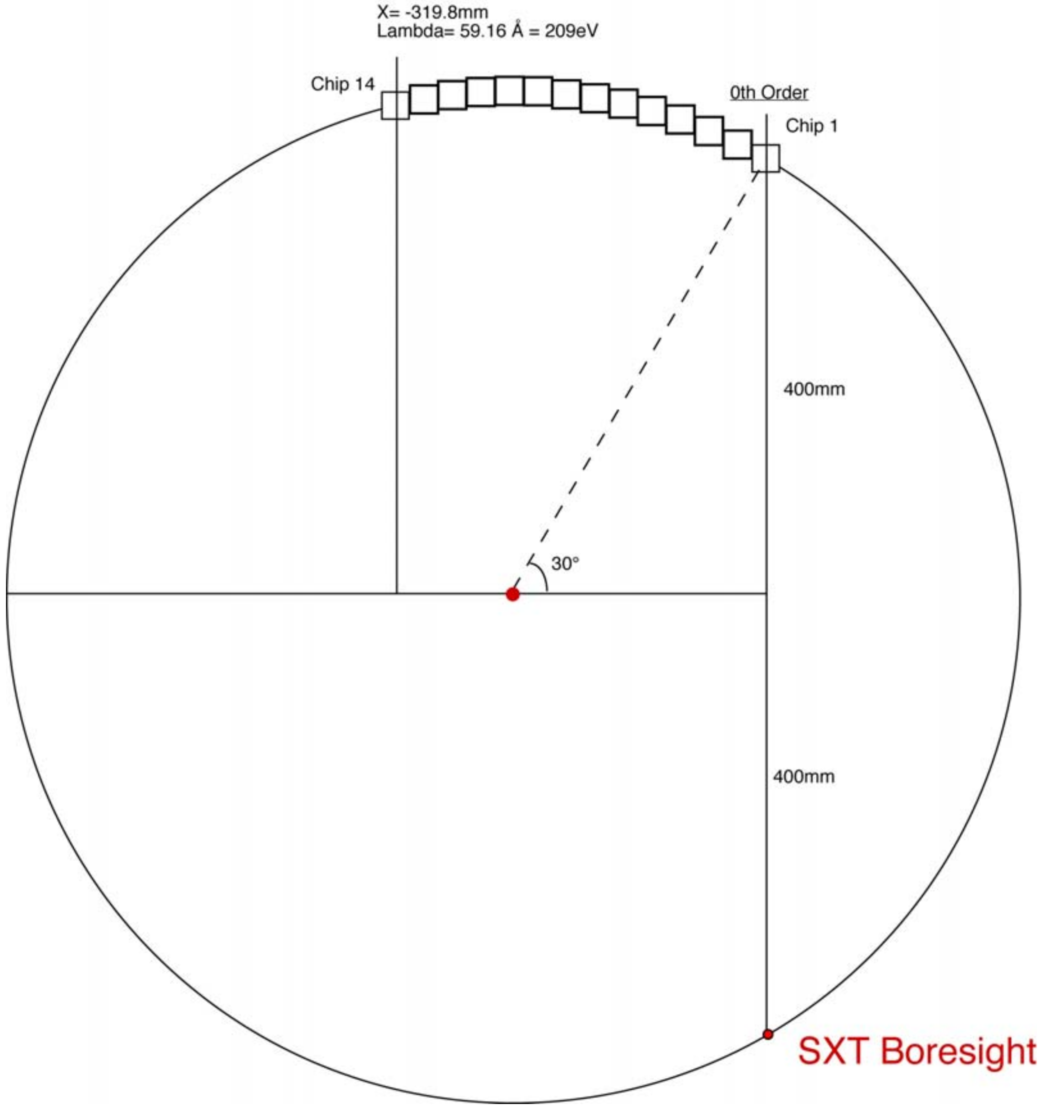
RGS Focal Plane Camera (RFC)



Reflection Grating Array (RGA)

(Geometry is highly exaggerated)

EDCCD Focal Plane Configuration for Off-Plane Grating (1 of 4 Focal Planes Req'd)



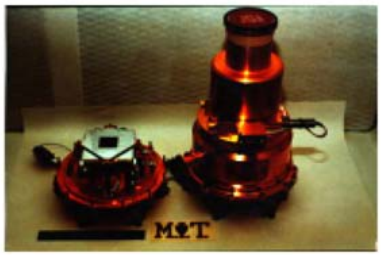
Major Challenge:

*•Requires **> 10x more** back-illuminated X-ray CCDs than any previous instrument (4 flight units +flight spares)*

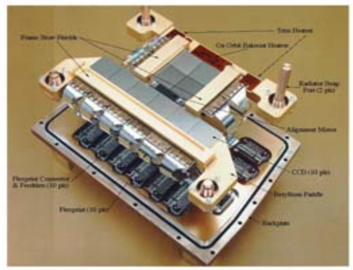
•Thus, high device yields are essential

RFC Flight Heritage

ASCA/SIS (1993)

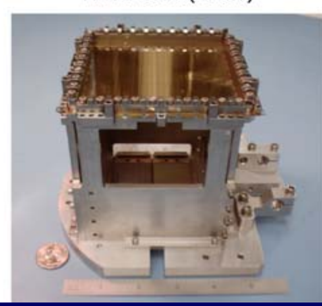


Chandra/ACIS (1999)



Astro-E2/XIS (2005)

HETE SXC (2000)



Key Technology Drivers

- High QE for 0.25 - 2 keV band
- High fabrication yield for back illuminated CCDs
- Adequate energy resolution at low E_x
  - Grating order separation
  - Particle background rejection
- Radiation tolerant at L2
- Reduced power & cooling
- Fast readout rate

RFC Requirements

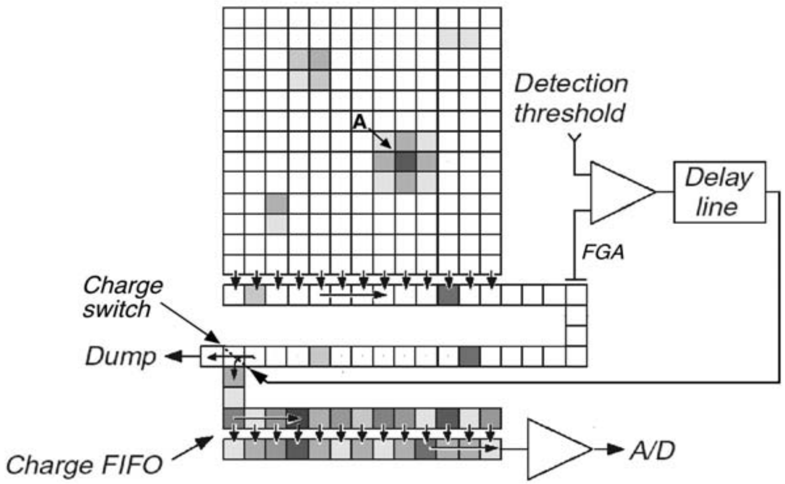
Derived RGS Focal Plane Camera Requirements		Derivation
CCD Quantum Efficiency @ 0.25 keV @ 1.25 keV	 0.78 0.99	Current allocations. Flowdown from area requirements. Includes transmission of the optical blocking filter and the CCD quantum efficiency.
Mass	33 kg	Current engineering allocation per telescope
Derived Requirements for Design		**Derivation**
Energy resolution at 250eV	< 70 eV FWHM	Required to separate spectra from overlapping orders
Stray light limitation	~ 1 photon t^{-1}_{frame} $A^{-1}_{superpixel}$ (300 nm < λ < 1100 nm)	Minimizes noise by limiting scattered sunlight, earthlight, and contaminant light from bright field stars
X-ray Transmission to CCD @ 0.25 keV @ 1.25 keV	 >0.88 >0.99	Current allocation for the OBF transmission.
Pixel size (microns)	~ 60 μm x 120 μm	15 μm * M (pix in column direction) x 15 μm * N (pix in row direction) Column and row summing to “super pixels” is required to critically sample the Point Response Function as a function of dispersed energy.
SRC readout length	≥ 290 mm	Required to cover the dispersed bandpass (0.25 to 2 keV) at designed spectral resolution. (14 chips @ 21 mm/chip)
SRC width in cross-dispersion direction	≥ 12 mm	Required to provide adequate detector areas for background subtraction
ZOC CCD format	Same as SRC chips	Identical to SRC chips to minimize costs
Frame readout rate	~ 200 Hz	Stray light and dark current reduction
Operating temperature	> -60 C	Dark current and flickering pixel reduction; improved radiation damage tolerance

RFC Event-Driven CCD (EDCCD) Technology: Motivation

- **Event-Driven CCD: Advantages**
  - Takes advantage of fact that only ~10^{-3} of X–ray CCD pixels contain signal charge in a frame time
  - Pixels are non-destructively sensed, and only those with signal charge are saved and digitized
  - Compatible with high yield BI processes

- **System Constraints relief for Constellation-X**
  - Lower power dissipation at a given frame rate (>100 x less)
  - Enables integrated flight camera testing at room temperature
  - Compatible with broad operating temperature range
  - Reduced shielding requirement (>10x more radhard)
  - High frame rate: relaxed S/C stability and jitter requirements

- **Additional Advantages of EDCCD**
  - Improved QE for 0.2 - 2 keV band
  - Uses thinner optical blocking filter (OBF)
  - High yields and reduced risk
    - Conventional MOS CCD processing
    - Compilation of separately-tested innovations
    - Key elements are flight-proven (ASCA, Chandra, AstroE2)
    - Conventional parallel register array
    - Low noise floating diffusion output amplifier



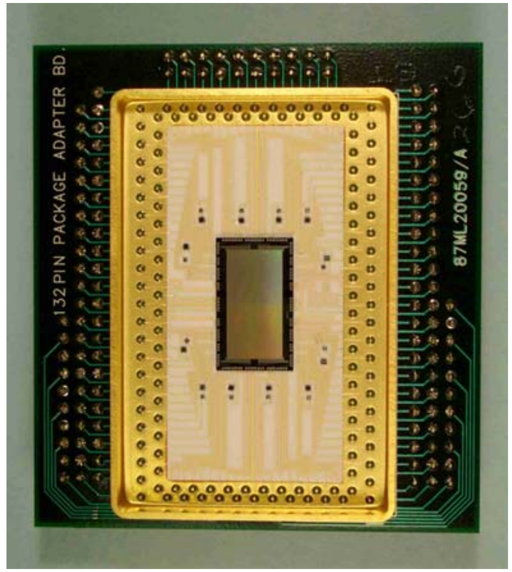
EDCCD Technology Status

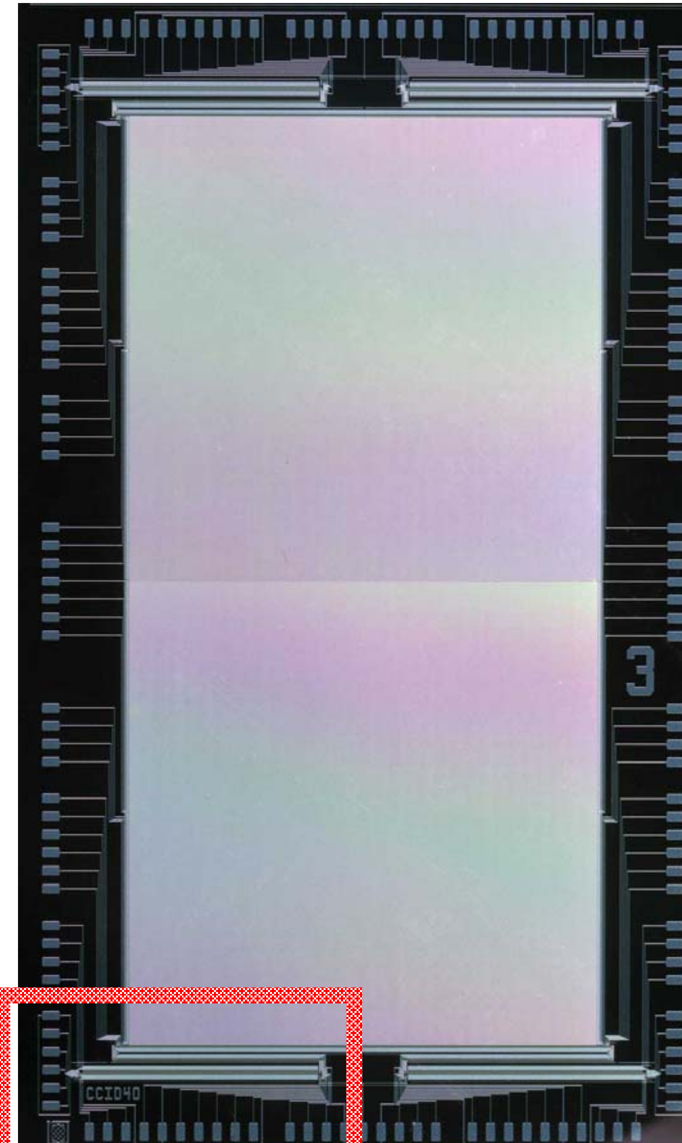
Gen 1-Lot 1 EDCCD

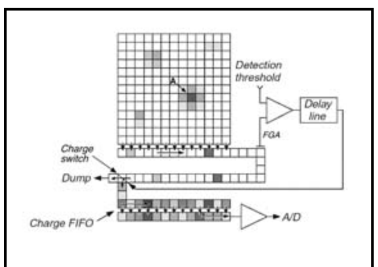
- 512 x 512
- FI & BI samples

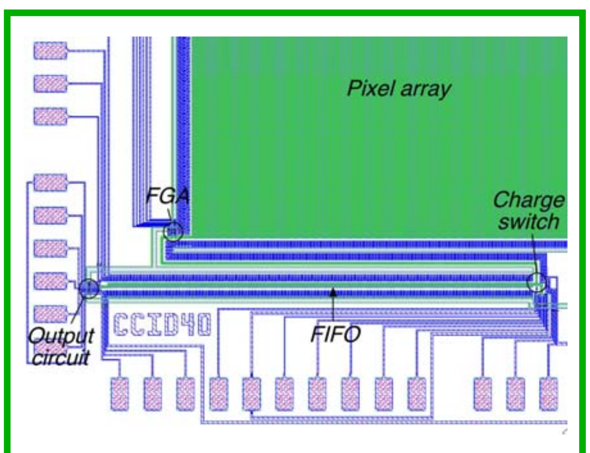
Gen 1.5-Lot 1 EDCCD

- New features and lot splits
- Hi-speed floating gate amp
- Hi-responsivity JFETs



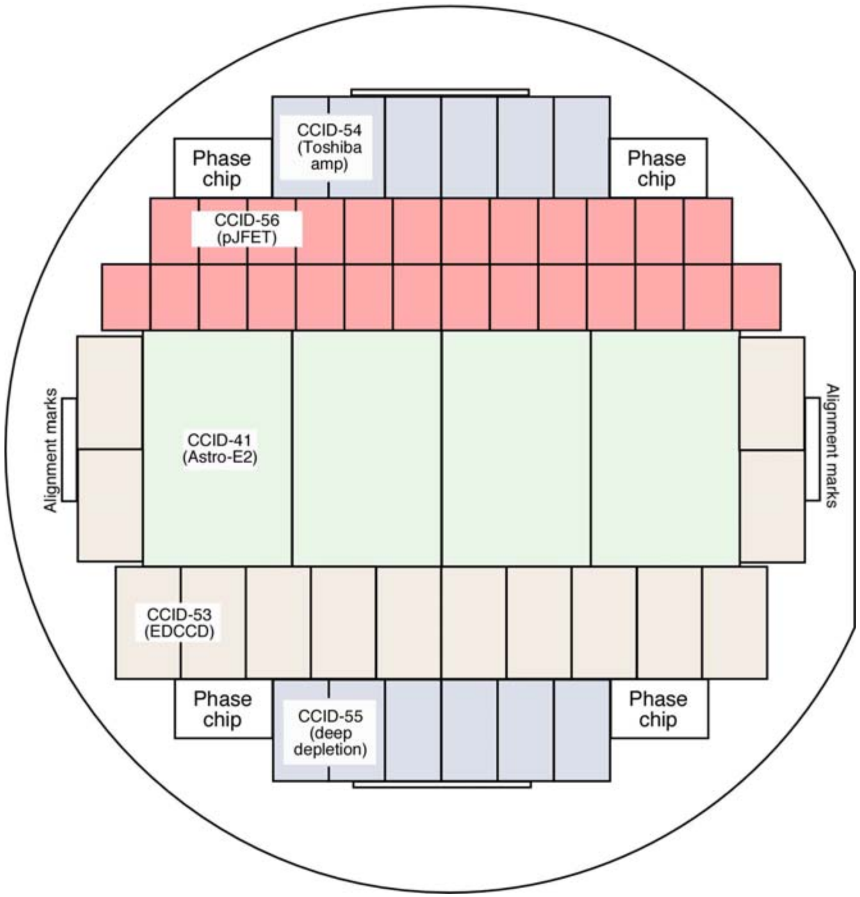




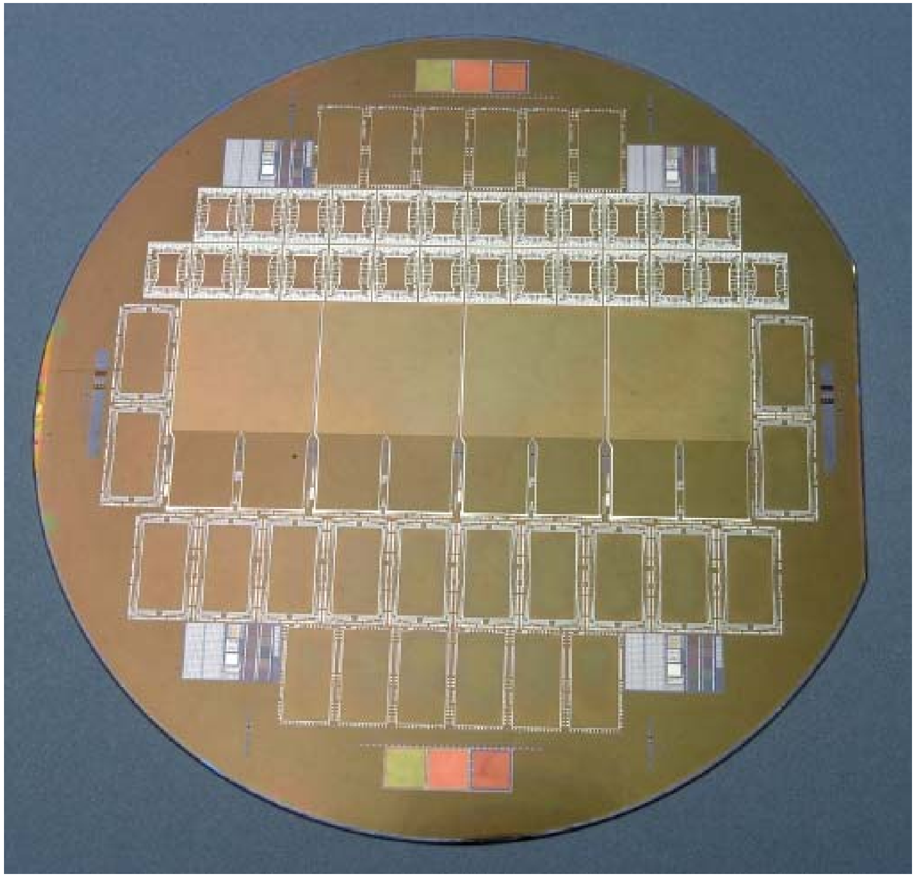


Gen 1.5-Lot 1 Wafer

Layout



Photo

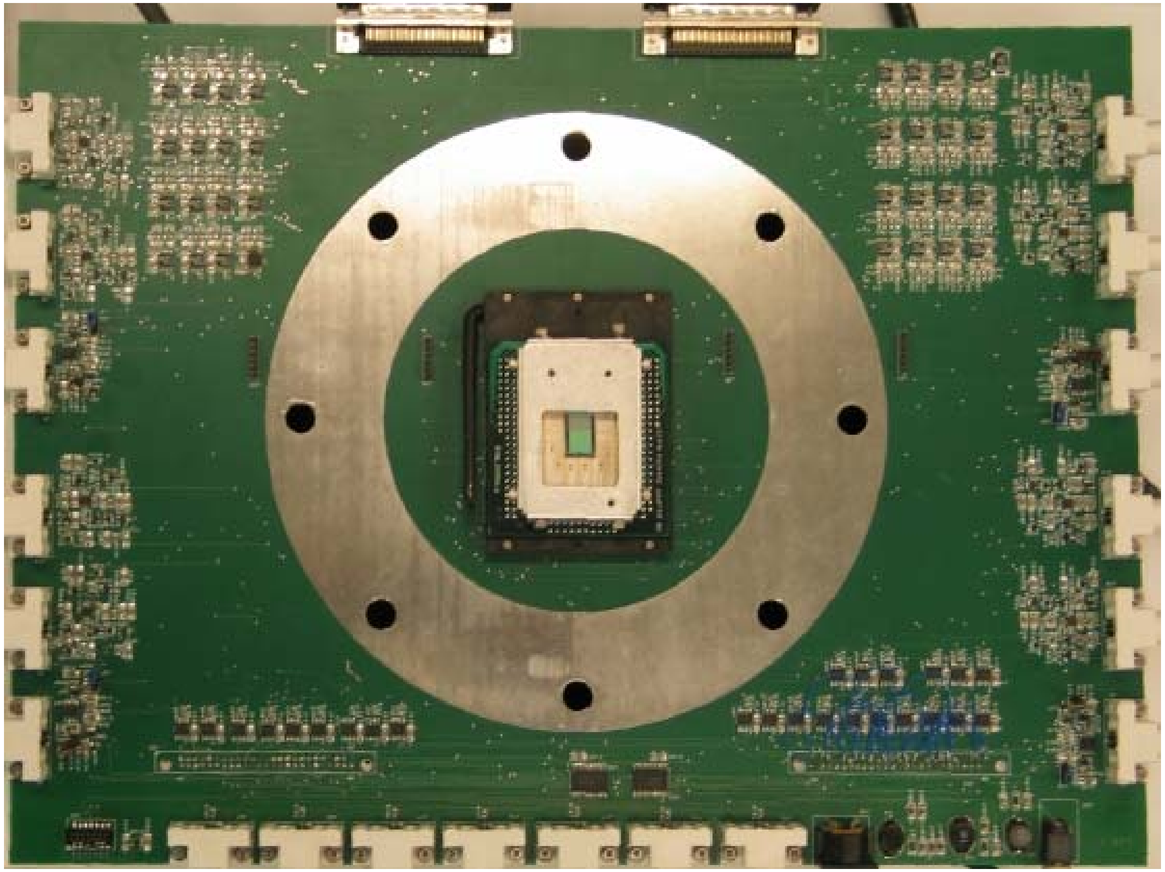


EDCCD Gen 1.5 Wafer Lot

- **Lot Features:**
  - Redesigned 512 x 512 EDCCD
    - 2 stage floating gate amp for event sensing (higher EDCCD speed)
    - 14 EDCCDs per wafer (cf: 4 per wafer for Gen 1)
  - Added test structures with:
    - High-speed, ultrahigh responsivity video amplifier (~100 μV per electron)
    - Revised p-JFET amplifiers
  - New planarized metallization technology
- **Gen 1.5 provided for:**
  - Transition step to full-up flight-scale devices
  - Wafer experiments to explore high speed, low noise structures required for >30Hz frame rate EDCCDs
  - Planarized metallization facilitates–
    - Reduced dark current at elevated device temperatures
    - High yield wafer layouts for elongated RGS readouts with reduced device counts

"Big Board" EDCCD Test Electronics

- *–Conventional parallel register clocking*
- *–Novel serial register drivers with pixel-cluster selection*
- *–Low noise confirmed*
- *–1 megapixel s^{-1} serial rate: 10x faster than previous MIT system record*
- *–Debugging in progress*

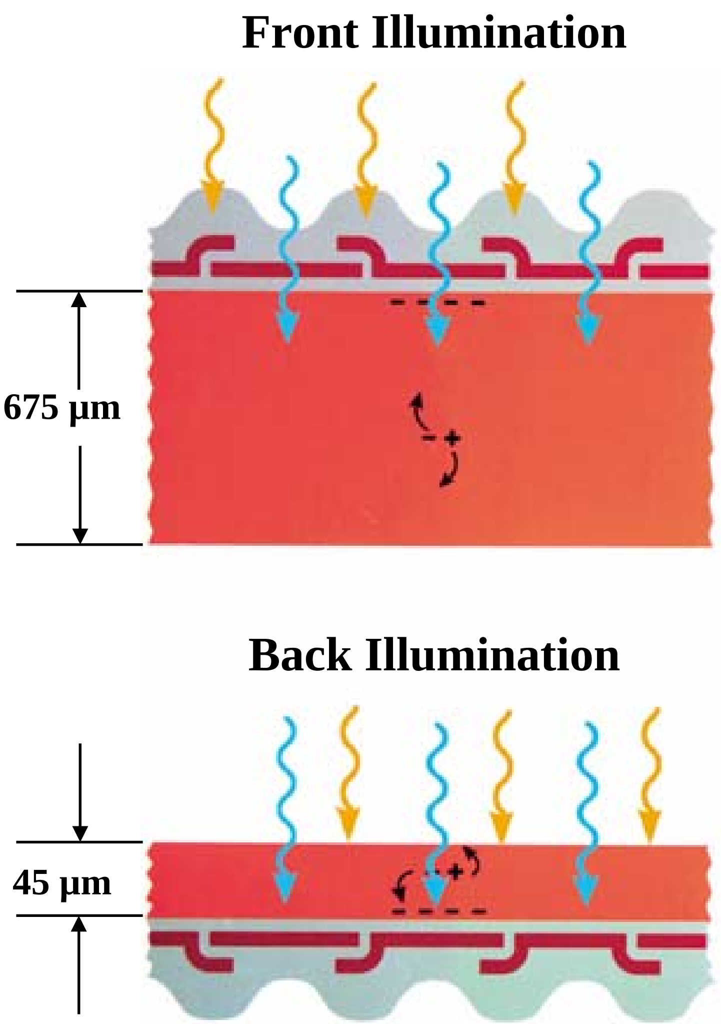


Fabrication Yield for X-ray CCDs

- High yield is needed to shorten fabrication phase and to reduce risk
- Yield for back-illuminated (BI) X-ray CCDs from Chandra was low: <1%
- New approach is needed to achieve goal of 20% yields for RFC

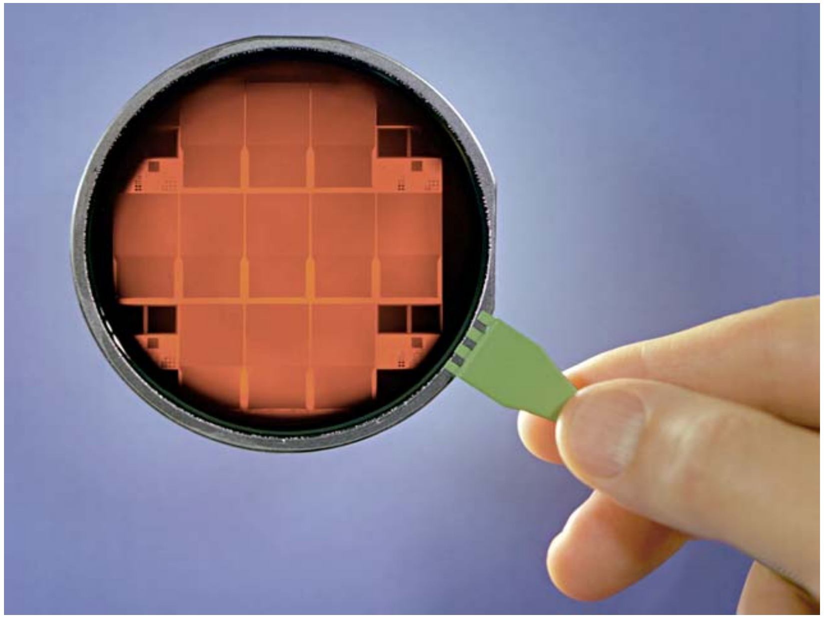
Back-Illuminated CCDs

- **Si thinned from backside after front-illuminated (FI) CCD is completed**
- **Collects electrons from x-ray photons**
  - **Absorbed in non-sensitive layers of FI devices**
- **Electrons lost to surface recombination**
  - **Special back surface processing**
  - **Produce electric field > 800 kV/cm (5×10^{12} e^-/cm^2) to drive electrons to buried channel of CCD**

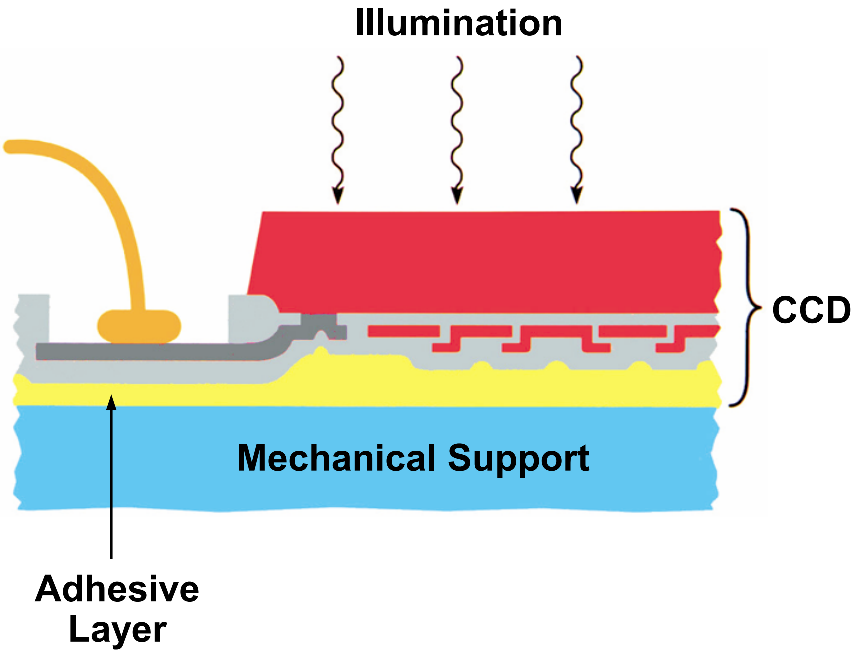


Fabrication of Back-Illuminated CCD Imagers

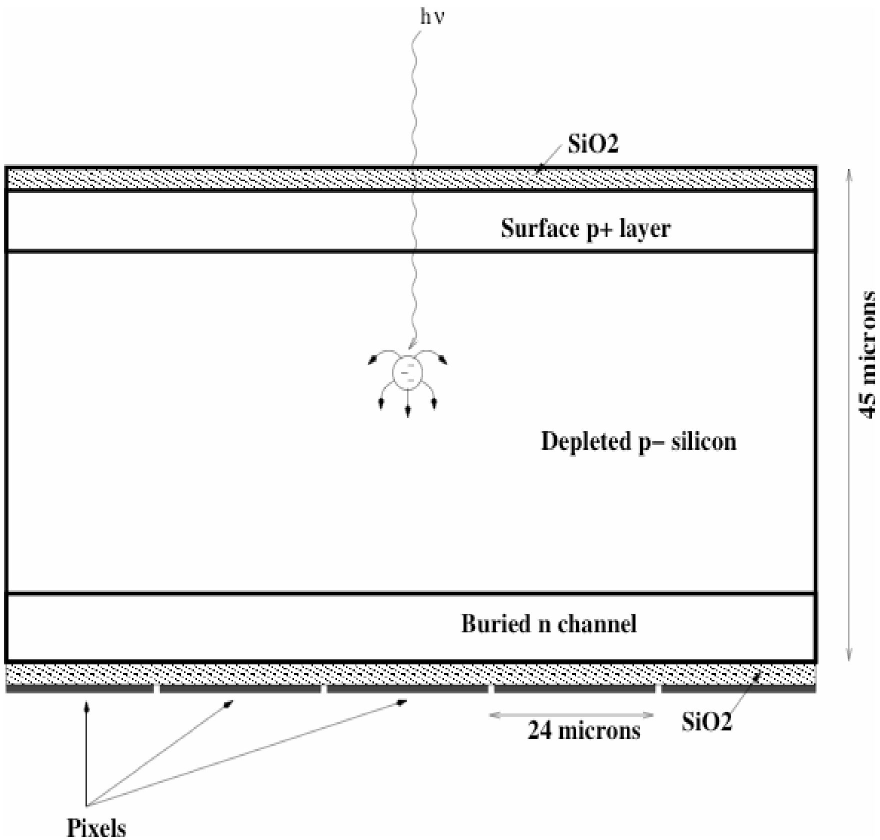
CCD Wafer with Center Chemically Thinned



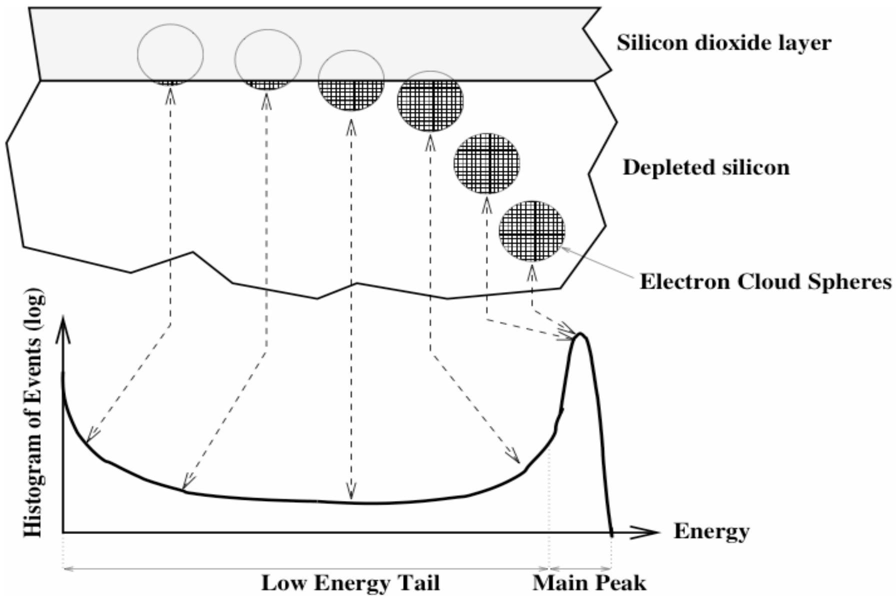
Thinned CCD Laminated to Supporting Wafer



X-ray Interaction Near Back Surface of Thinned BI CCD



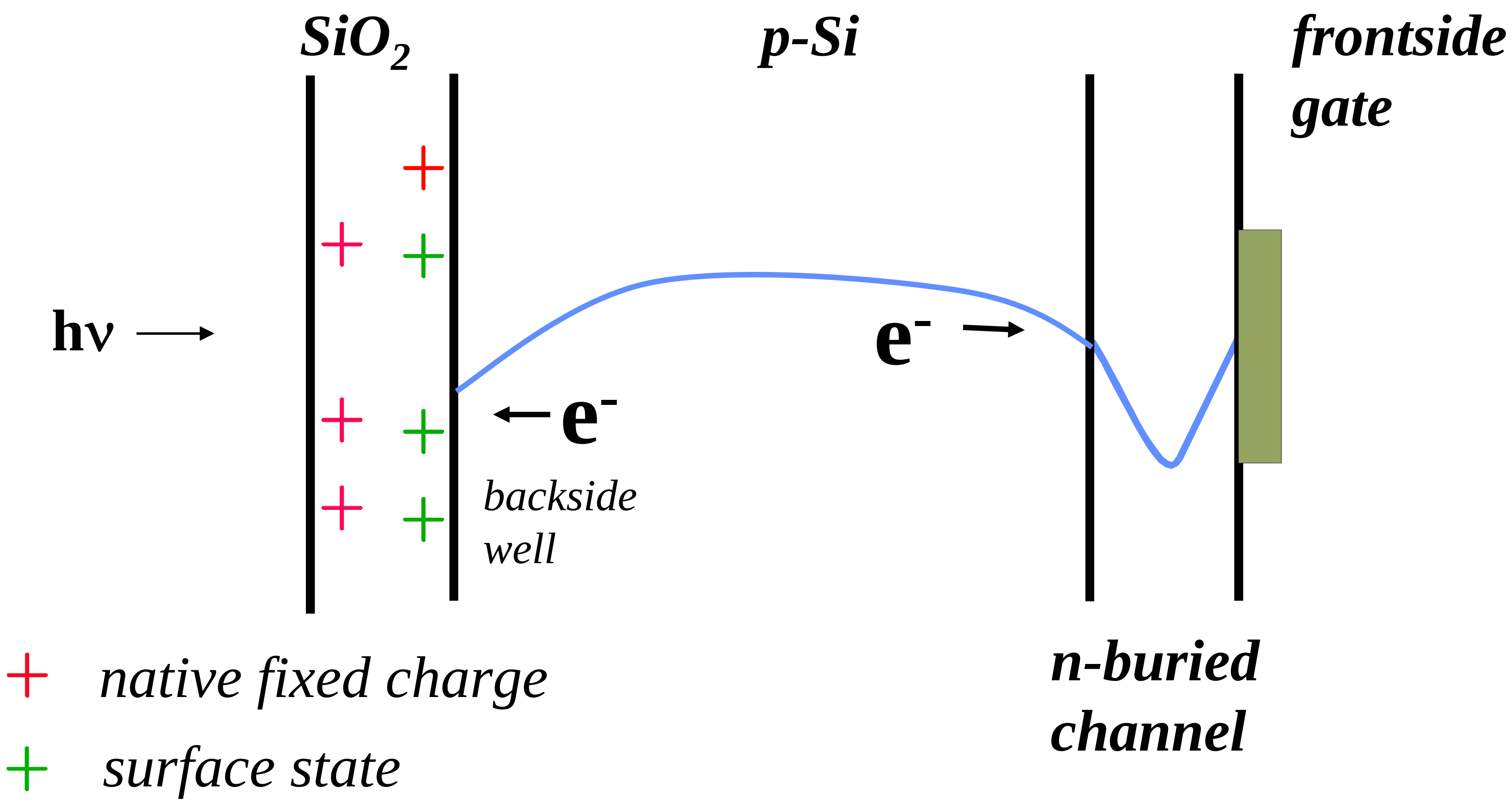
Cross Section of BI CCD



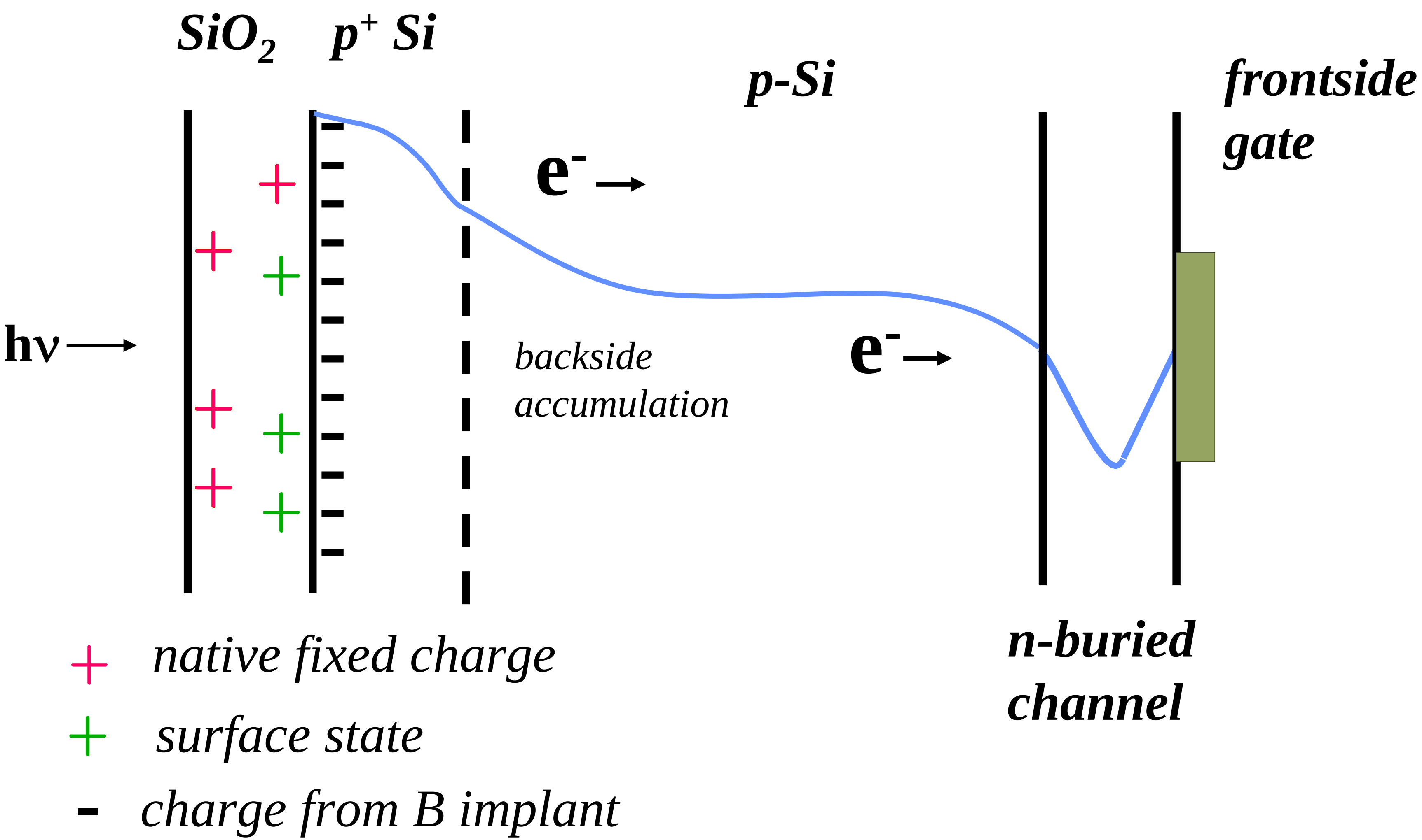
Impact of Charge Cloud Diffusion

Loss of charge near back surface impacts both energy resolution and quantum efficiency!

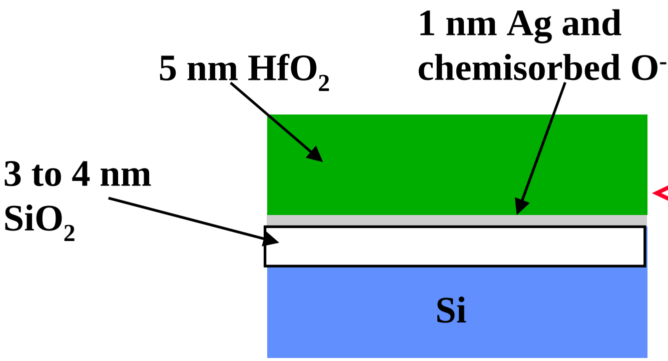
CCD Native Oxide Potential Well



MBE CCD BI Potential Diagram

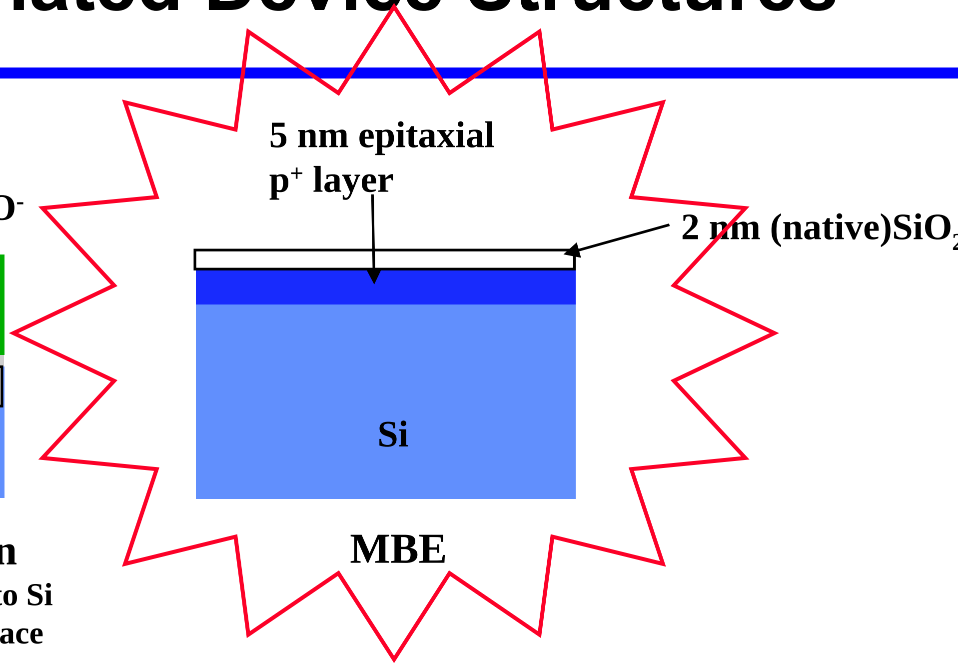


Back-Illuminated Device Structures

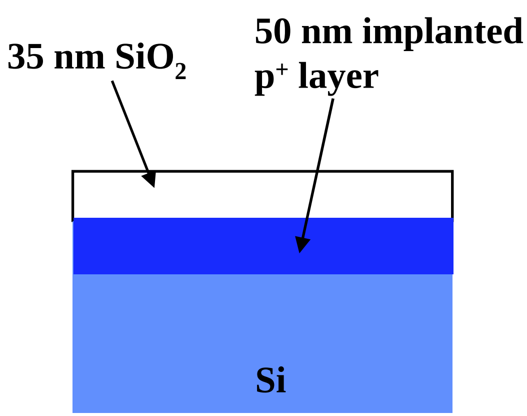


Charge Chemisorption

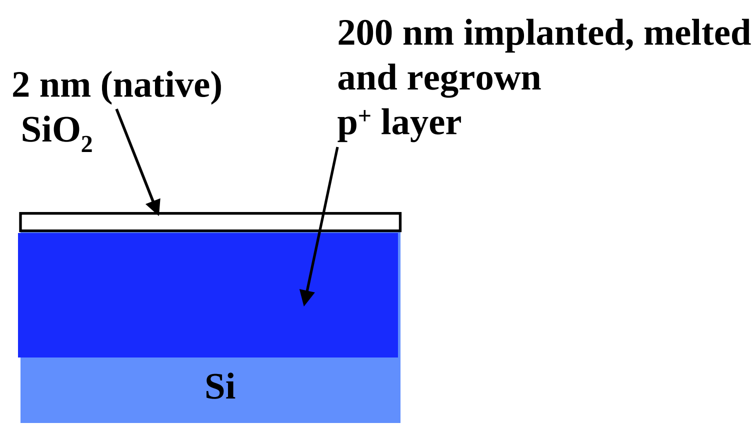
Charge distribution is external to Si
Higher Electric Field at Si Surface



MBE



Refractory

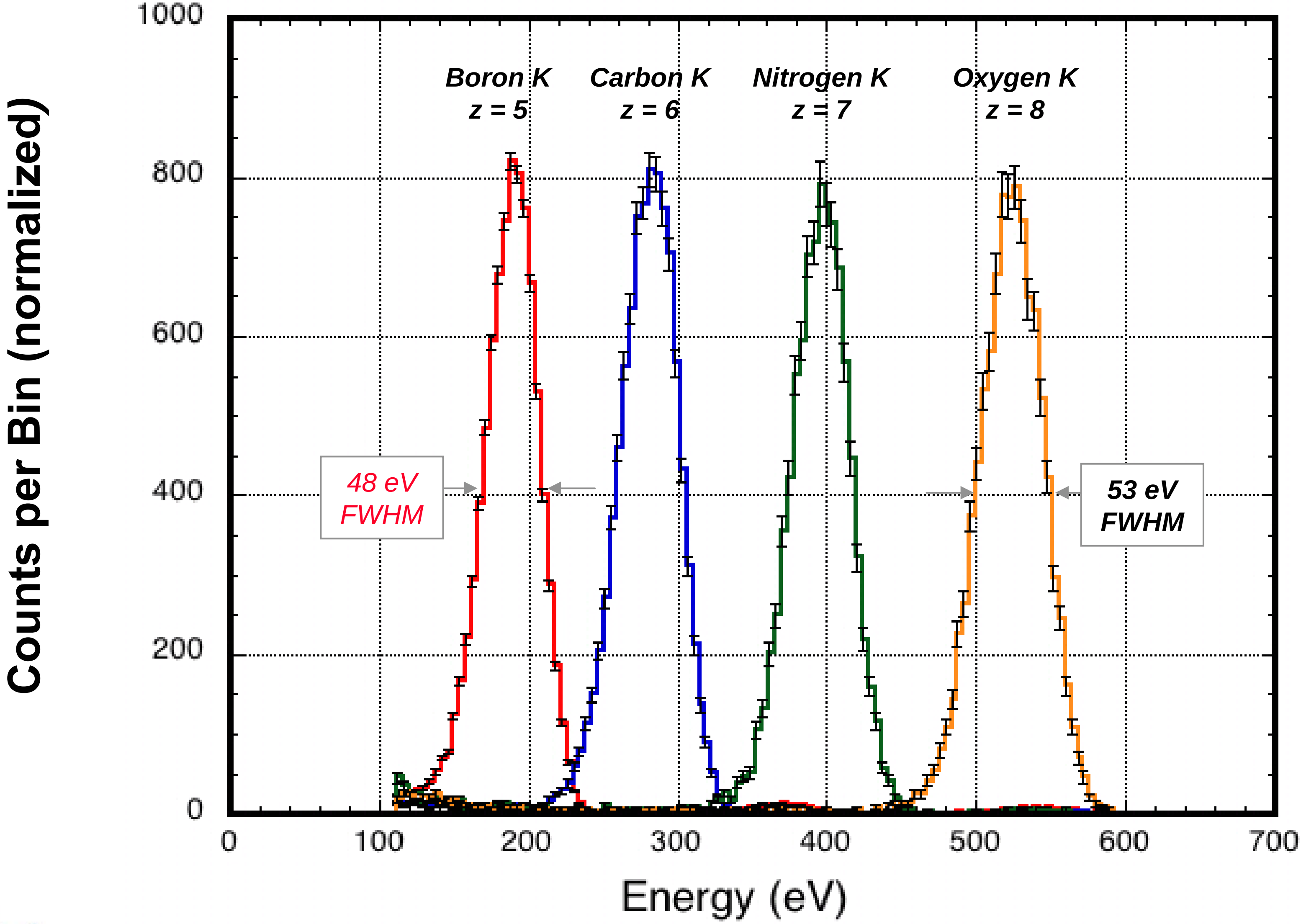


Ion Implant, Laser Anneal

Breakthough in BI CCDs: New MIT/LL High Yield Process

- **Molecular Beam Epitaxy (MBE) process developed in-house provides *high yields***
  - Comparable to chemisorption: ~10% even with initial "learning curve"
  - Further refinements should raise yields to ~20% or greater
  - Dark current is less than half that of chemisorption BI processes
  - No reliance on outside vendors or licensed technologies
- ***Excellent resolution* at both low and high energies**
  - Con-X RFC goals met for $0.2 < E_x < 2.0$ keV
  - X-ray spectra superior to those from chemisorption-charged (CC) devices (Astro-E2/XIS)

MIT/LL CCID48 :
Best Ever Measured Photopeak Resolution in MBE BI X-ray CCD

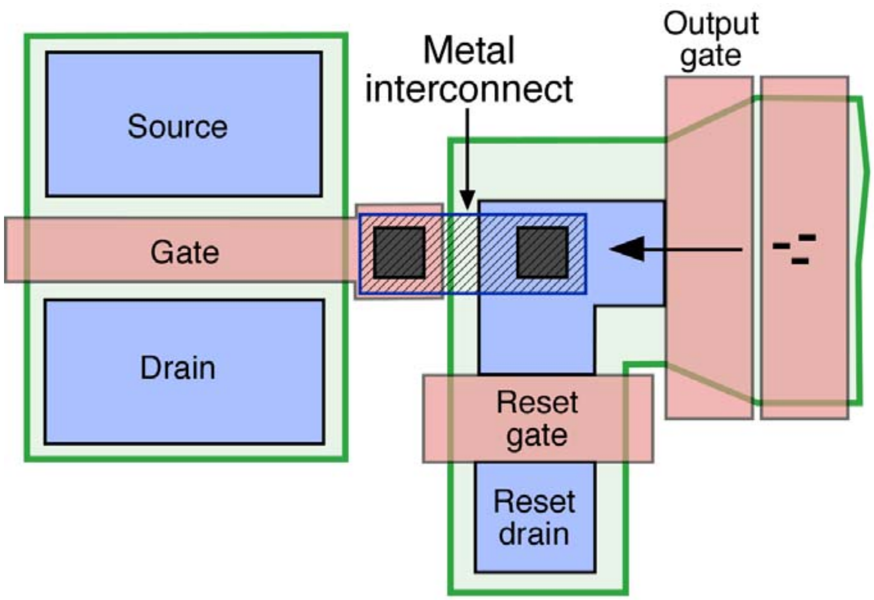


Breakthough in BI CCDs: New MIT/LL High Yield Process--con't

- Boron and Carbon K photopeak symmetry imply excellent quantum efficiency
  - Collection fields must be strong, with excellent charge collection from near back surface
  - Anticipate QE comparable to RFC "plausible model"
  - Absolute calibration will require reference to new BESSY-calibrated standard CCDs
- Excellent process integration
  - Can be applied to previously-fabricated FI wafers
  - Well-understood, moderate temperature (~400 C) processing results in low surface states and low dark current
  - Aluminum OBF can be deposited in same facility
  - Fully compatible with EDCCD fabrication

MIT CCD Outputs: Layout Comparison

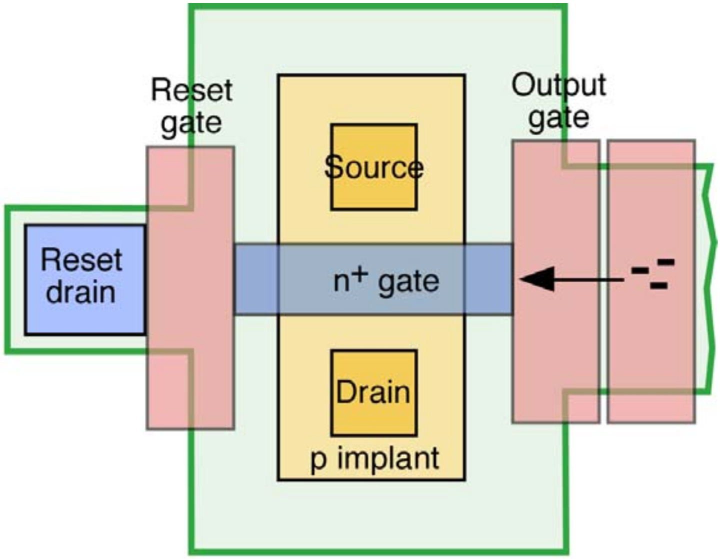
Standard (ACIS, Astro-E2)



Standard output (n-MOSFET)

20 µv/e-

New (Con-X Gen 1.5)

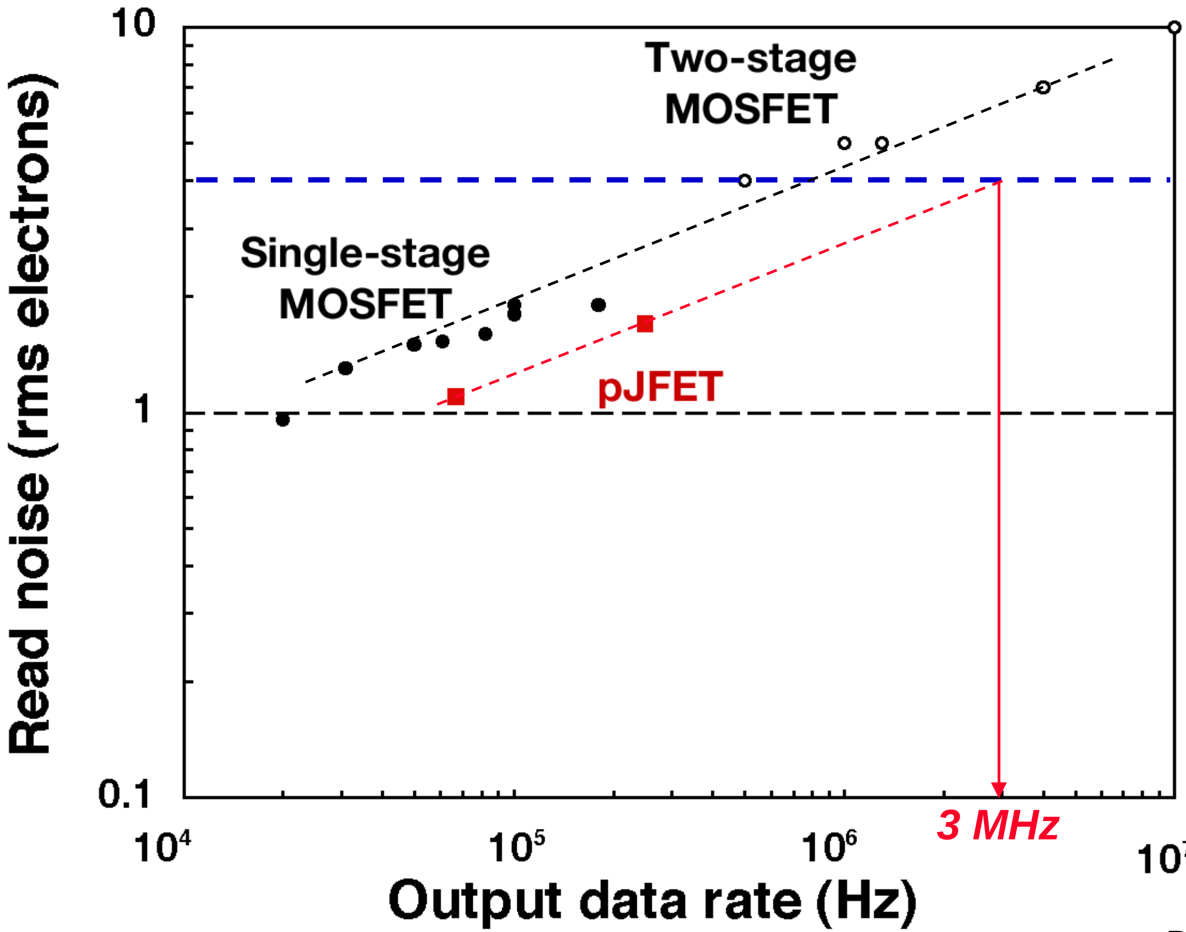


P-channel JFET output

30 µv/e-

Burke, B. E. et. al 2006 (in prep)

Noise Comparison: Standard MOSFET vs New JFET Output



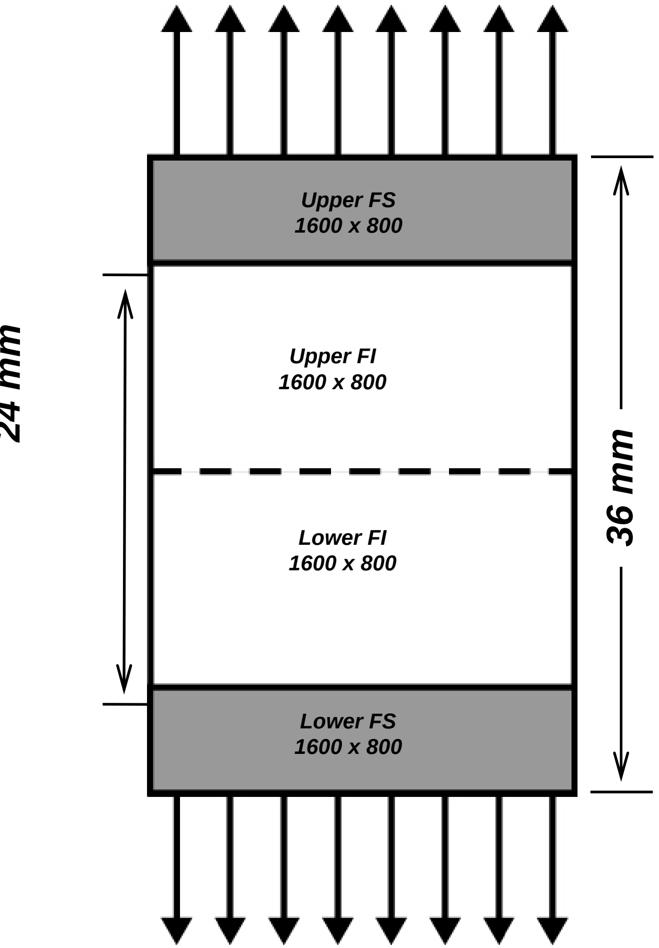
4 e^- RMS

➡ < 40eV FWHM Contribution

New JFET output can operate ~4 times faster at a given readout noise

Burke, B. E. et. al 2006 (in prep)

Configuration of Proposed Flight EDCCD Detector



- **Baseline EDCCD Imager**
  - Frame Imager (FI): 24 mm x 24 mm
  - Frame Stores(FS): 2 regions (top and bottom) @ 24mm x 6mm
  - Basic pixels: 15µm x 15µm in FI; 15µm x 7.5µm in FS
  - FI format: 1600 x 1600
  - Summing of basic pixels to "superpixels" that match PSF
    - e.g. 4 cols x 8 rows => 60µm x 120µm
  - Readouts: 16 (8 along top + 8 along bottom)
- **Clocking**
  - 200 Hz frame rate for 60µm x 120µm "superpixels"
  - Serial rate: 1 MHz per readout
- **Array adaptations**
  - Two-sided abuttable; <1 mm gap loss
  - Tailor "superpixel" dimensions along array to match energy-dependent spectral PSF while providing desired oversampling
  - Graded Al OBF thickness with chip distance from ZOC
  - Anticipate <0.1% bad pixels, based on Chandra and Astro-E2 experience

Straylight Specification and OBF Requirement

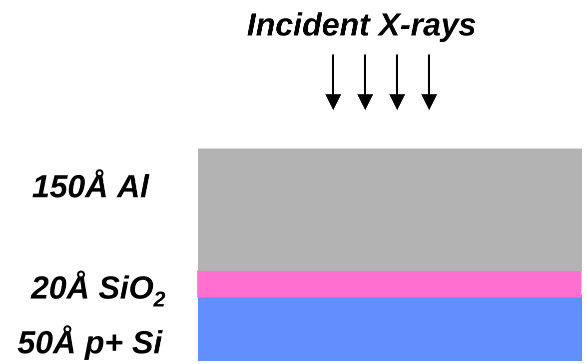
- For minimal contribution to the electronic noise we want

  1 photon t_{frame}^{-1} $A_{superpixel}^{-1}$ in 3000-11000 Å optical band

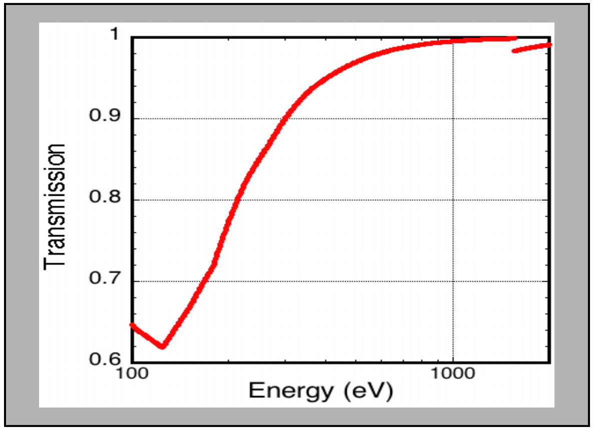
Mission	t_{frame}	$A_{superpixel}$	FOM= t_{frame}^{-1} $A_{superpixel}^{-1}$
XMM-RGS	0.6 s	27*27*3*3 μm^2	2.54 x 10^{-4} s^{-1} μm^{-2}
ConX-RGS	0.005 s	15*15*4*8 μm^2	2.78 x 10^{-2} s^{-1} μm^{-2}

- From table, Con-X RFC is 100 times less sensitive to straylight than the XMM-Newton RFC
- This has the following implications for the OBF:
  - We assume that Con-X can achieve the same straylight performance as did XMM
  - Since the Con-X-RFC FOM is ~100 times better than that of XMM-RFC, then the ConX-RFC needs 100 times less optical blocking.
    - 300 Å of Al reduces optical straylight by a factor of 100
    - XMM-RFC OBF is 450 Å thick.
    - Con-X RFC OBF can be 450 Å - 300 Å = 150 Å thick.
  - For minimal noise contribution we assume 150 Å of aluminum is sufficient. The current reference design carries 100 Å of aluminum. Increasing the OBF to 150 Å will decrease the x-ray transmission (and throughput) by ~6%
    - T_{100}/T_{150} = 0.897/0.850 = 1.06

X-ray Quantum Efficiency: Contributing Factors…

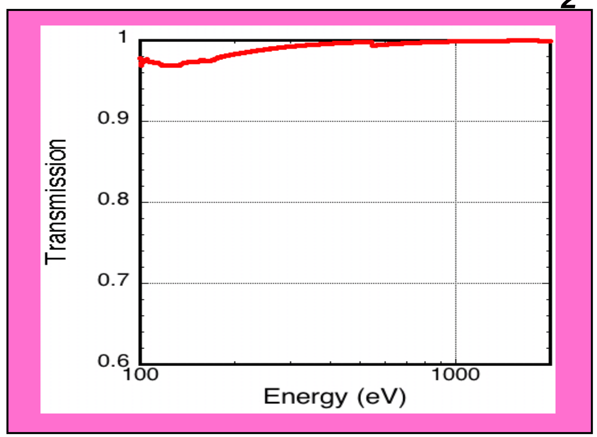


Al



SiO_2

*



p+ Si

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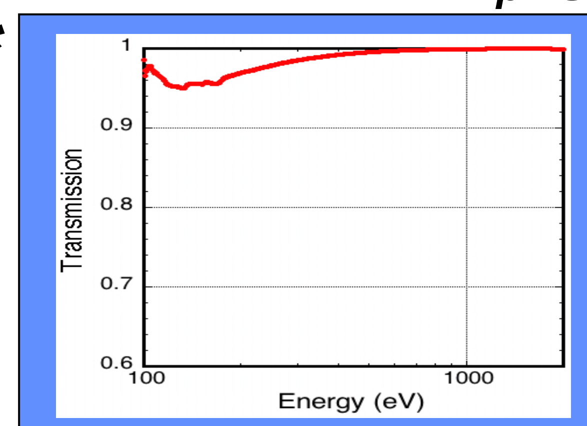


Al OBF thickness is the dominant factor is QE

Development Goals for Successive EDCCD Generations

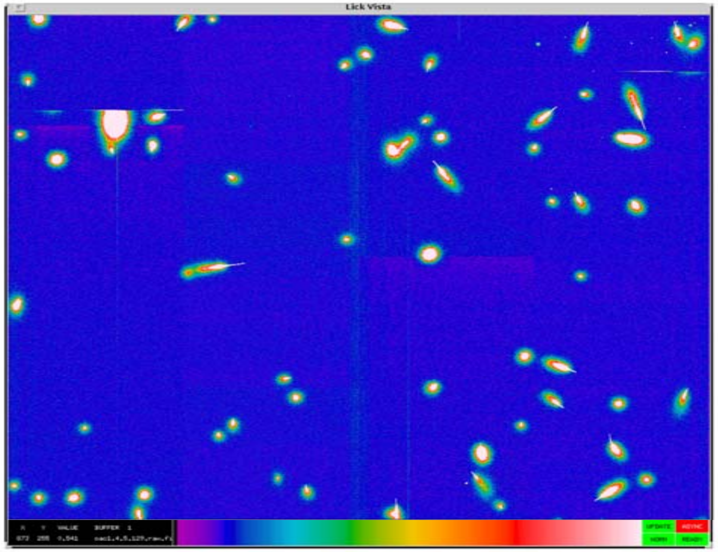
- **Generation 1**
  - Gen 1–Lot 1: First EDCCD that featured event-driven output, resulting in greatly increased frame rate.
- **Generation 1.5**
  - Gen 1.5–Lot 1: Improved output circuitry, allowing faster readout speed.
- **Generation 2**
  - Gen 2–Lot 1: Enlarge CCD format to flight configuration (1600 x 1600).
  - Gen 2–Lot 2: Demonstrate very thin on-chip OBF, leading to significant QE improvement.
  - Gen 2–Lot 3: Establish robust BI processing, perfect Si-SiO_2 interface quality, and push limits on the OBF thickness to further improve QE.

Backup Slides

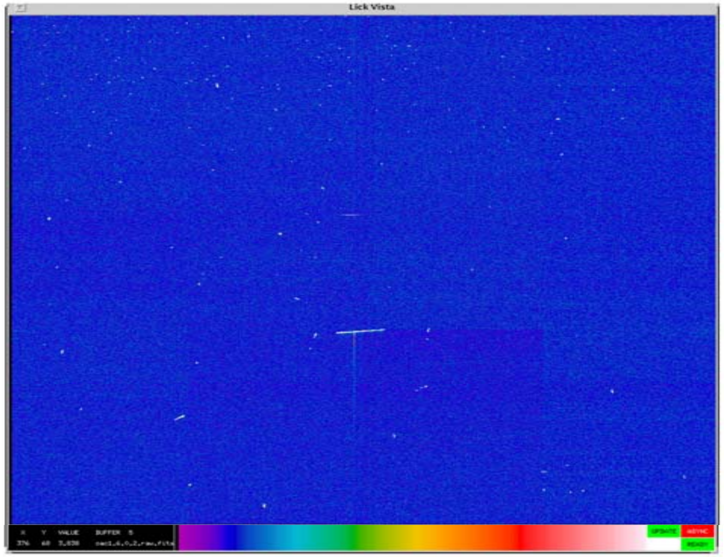
Motivation for the Event Driven CCD

- Pixels with Signal Charge are Sparse in X-ray Astronomy Images
  - –Most are particle-induced background pixel clusters
  - –Chandra experience suggests a more optimal pixel selection approach

FI=Front-illuminated CCD S2 = w182c4r



BI=Back-illuminated CCD S3 = w134c4r



—Pixels with charge above threshold in 3.3 s exposure—

FI: 26278 out of 1,048,576 pixels = 2.5% **BI: 970 out of 1,048,576 pixels = 0.09%**

- Only ~10^{-2} to 10^{-3} of pixels contain signal charge.
- Event-driven CCDs digitize only those pixels with signal charge

⇨ ***100 - 1000 x faster readout for a given power***

How has the MBE "Revival" come about?

- Improved MBE facility process control at MIT/LL
  - Relocation of residual gas analyzer
  - Use of electron impact energy spectrometer
  - Documentation of lot-to-lot procedures
- Yield gradually improved over successive lots
- Improved understanding of deposition rate effects
- Improved ability of technical staff to utilize MBE theoretical models

RGS System Level Requirements

RGS Requirements		Trace to Mission Top-Level Requirements
Bandpass	0.25-2.0 keV (6 to 50 A)	In combination with XMS, meets spectral resolution requirements over the 0.25 Š 10 keV bandpass. Provides overlap region for cross-calibration with XMS
Spectral resolving power,R ($\lambda/\Delta\lambda$)	$\geq$300 below 1 keV	Meets TLRD baseline requirement for R
Effective Area (each telescope) @0.25 keV @0.60 keV @1.25 keV	 250 cm^2 250 cm^2 175 cm^2	Flowdown from mission baseline effective area requirement
Mass	106 kg	Mass Allocation per telescope
Derived Requirements		
RGA Throughput Efficiency: @0.25 keV @0.60 keV @1.25 keV	 0.26 0.15 0.06	Includes array structural blockage, vignetting, grating edge obscuration, and grating diffraction efficiencies.
RFC Throughput Efficiency: @0.25 keV @0.60 keV @1.25 keV	 0.78 0.95 0.99	Includes the transmission of the optical blocking filter and the CCD quantum efficiency

Technology Readiness Levels (TRLs)

- TRL 9: Actual system “flight proven” through successful mission operations
- TRL 8: Actual system completed and “flight qualified” through test and demonstration (ground or space)
- TRL 7: System prototype demonstrated in a space environment
- TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 5: Component and/or breadboard validation in relevant environment
- TRL 4: Component and/or breadboard validation in laboratory environment
- TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 2: Technology concept and/or application formulated
- TRL 1: Basic principle observed and reported